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Characterization of Groundwater in the Basaltic Fractured Rock Aquiferous Formations of the Limbe Coastal Region of Mount Cameroon, SWR-Cameroon

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Abstract

Limbe is the capital of Fako Division in the South West Region of Cameroon. It is an economic centre for Agro-industries, the Limbe deep seaport and has the only oil refinery (SONARA) in the Cameroon. It is an area where the groundwater is becoming increasingly the most important water resource as the exponential population growth imposed by urban migration towards the Agro-Oil-Port city has out-paced the development of water supply infrastructure. There are little or no funds allocated to carry out research on the rock/groundwater interactions and groundwater quality of the phreatic aquiferous formations in Limbe Coastal Region of Mount Cameroon. This study was carried out to characterize the groundwater solute chemistry and groundwater domestic-agro-industrial quality using hydrogeochemical tools and physicochemical parameters; Ionic ratios, Gibbs's diagram's, Piper's diagrams, Durov's diagrams and water quality indices. From field physicochemical parameters; wet season, pH range from 6.1-8.5; Temperature, 22.3-27.9°C; EC, 38-963µS/cm; TDS, 25.46-645.21 mg/L and dry season pH values ranged from 6.4- 7.8; temperature, 24.1-30.4oC; EC, 59-1515µS/cm; TDS, 39.53-1015.05 mg/L. Forty groundwater samples; 20 per season, wet and dry were analysed. The major ions fell below WHO acceptable limits for both seasons. The sequence of abundance of major ions are Ca^{2+}>K+>Mg^{2+}>Na^{+}>NH^{4+}, HCO_3 >Cl^{-}>HPO_4^{2-}>SO_4^{2-}>NO_3^{-}in wet season and Ca^{2+}>K^{+}>Mg^{2+}>Na+,HCO_3 >Cl->SO_4^{2-}>HPO_4^{2-}>NO_3^{-} dry season. Groundwater ionic content was as a result of ion exchange fromrock weathering reactions. Water types are $MgHCO_3$, CaCl and NaCl in wet season $MgHCO_3$, $CaHCO_3$, CaCl and NaCl in dry season. The hydrogeochemical facies are $CaMgHCO_3$, Ca-Mg-Cl-SO_4 and Na-K-HCO_3 in the wet season and Ca-Mg-HCO3 in dry season. Ion exchange, Simple dissolution and uncommon dissolution determined groundwater character. HT wet season 5.04-531.95mg/L, 91.50-570.61mg/L dry season;WQI wet season 2.85-307.31, dry season 1.04-272.43; RSC wet season -7.79-2.33, dry season -2.99-0.82; %Na wet season 8.56-53.56, dry season 1.67-13.41; KR,<1 for both seasons; MAR wet season 24.33-100, dry season 32.12-72.29;SAR for wet season 0-0.1, dry season 0.0027-0.068; PI wet season 0-2100, dry season 28.57-51.91 and the Wilcox diagram; excellent-good for irrigation purposes.Some physicochemical parameters exceeded the permissible limits. There is seawater intrusion into this coastal aquifer during wet season.

Keywords: Basaltic Fractured rock; Characterization; Groundwater-quality; Hydrogeochemical-facies; Limbe-Cameroon

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Introduction

Limbe the Fako Divisional headquarters of the Southwest Region in Cameroon is situated between 3.96-4.06N and 9.15-9.24 Eshown in figure 1. As an urban town with over 130,000 inhabitants [1] and insufficient water supply by the national water supply company CAMWATER, the inhabitants are obliged to turn to other sources of water such as natural springs, community water project catchments, hand-dug wells and boreholes. The inhabitants of parts of Limbe have always complained of low quality of drinking water from wells during the rainy season as such, there was a need to carry out this research to determine the root cause of this loss of quality during the rainy season. With the population explosion and the increased need for groundwater for economic development such as agriculture, industrial and domestic activities, understanding the groundwater chemical character and the aquiferous formations through which this water flows is of great importance for the future development of this region and sustainable use and protection of this aquifer system.

Climate

Limbe experiences a subequatorial climate (hot and humid throughout) with mainly two distinct seasons; a rainy season between April to October and a dry season from November to March with a mean annual rainfall of about 3,100 mm, ±1,100 standard deviation [2]. The annual rainfall is high, with yearly precipitations varying from 1,500 to 6,000 mm in the last 34 years for different stations. Peak rainfall is recorded from June to August or September. June and July are characterized by intense and short-lived rainfall usually lasting less than 5hours a day. Whereas, August and September tend to experience less intense but more prolonged rainfalls that can last for

4 to 5 days in a row. Monthly rainfall totals frequently attain over 500 mm and sometimes up to 1,000 mm in June, July and August. The mean annual temperature is ~26 °C and shows only limited variations of ~4° throughout the year. Humidity is generally above 85%. These characteristics correspond to the Tropical Monsoon Climate according to the Köppen climate classification scheme [3,4].

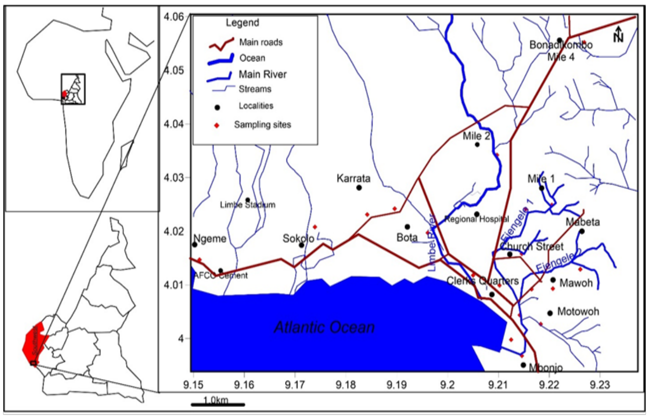

Figure 1: Map of the Study Area, Limbe-Southwest Region Cameroon.

Drainage

Limbe and Ejengele are the two main rivers in Limbe with the former being the largest. Limbe River takes its rise from Mt Cameroon, through Mile 4, Mile 2, Middle farms, Botanic Garden and into the Atlantic Ocean. Limbe River has a trellis drainage pattern with all its numerous tributaries running parallel down the slopes of Mount Cameroon. The slopes are steep, up to 43%, causing the streams to flow with high velocities. Other smaller streams consist of: Mange, Sange-Mile 4, Grand Lake-Mile 2, Konkikar, Balimba-Mabeta New layout, Motowoh water and Ndiba water. There are numerous springs notably: Likomba, Toma-Mile 4, Busumbu spring-mile 2, Cold source Mile 1 and Crystal garden. Gravity catchments have been constructed around some other smaller springs for additional water supply; Mile 4, Mabeta, Mawoh, Motowoh, Batoke. The serivers empty into the Atlantic Ocean.

Geology

Limbe sits on the plains and south eastern slopes of the ridge of Mount Cameroon separating the Rio del Rey and Douala basins; the Cameroon Volcanic Line presented in figre 2. The geology of Limbe is volcanic being consequent of the eruptive events of Mount Cameroon. The geology is of tertiary basaltic rocks composed of multiple porphyritic basaltic lava flows, punctuated by several strombolian pyroclastic cones to the West and North West and lahar deposit to the East seen in figure 2. These rocks either lie exposed at the surface or are covered by extremely fertile dark brown, reddish brown, yellowish and/or pale yellow sticky, clay, silt and silty clayey soils derived from intense in situ weathering. Soil thicknesses range from a few centimeters tomore than 10 m [2]. The mineral content of basalts in Limbe consists mainly of Clinopyroxene ($Ca(TiMgAl)\ SiAl)_2O_6$), Hematite (Fe_2O_3), and Goethite ($FeO(OH)$ and the soils comprises mainly of Anatase (TiO_2), Annite ($KFe_3AlSiO_{10}(OH,F)_2$), Augite ($Ca_2(Al\text{-}Fe)_4(MgFe)4Si_6O_{24}$), Goethite, Hematite, and Kaolinitic ($Al_2Si_2O_5(OH)_4$) minerals.

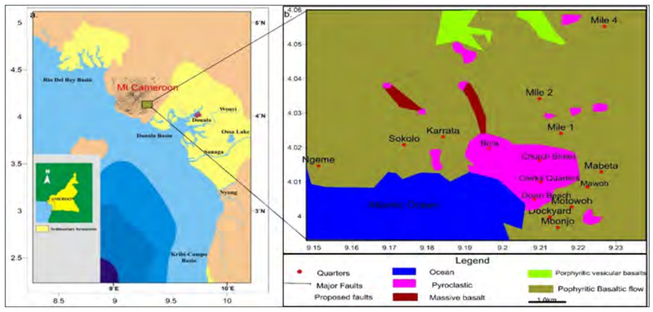

Figure 2: Sedimentary basins sandwiching Mount Cameroon and location of Limbe b. Geologic Map of Limbe and Environs, indicating the main geomorphologic characteristics, trend of the hydrographic network and morphology of some pyroclastic cones [2].

Geomorphology

The topography is marked by ridges and deeply incised ravines with a general W-E orientation, at high angle to the general NE-SW orientation of Mt Cameroon and gently sloping foot slopes of Mt Cameroon. These ridges form part of the Limbe-Mabeta volcanic massif, made up of degraded and deeply weathered Tertiary basaltic lava flows [5] The Limbe-Mabeta massif is an eroded volcanic massif SSE of Mt Cameroon. It is characterized by a series of sub-parallel E-W oriented valleys bordered by the 170°-striking Om be structure on its Eastern side [6]. Individual ridges are separated by asymmetric V-shaped valleys occupied by perennial and/or ephemeral streams. These streams either empty themselves directly into the ocean or into the delta around Mabeta.

Hydrogeology

Very little work has been done on the hydrogeology of Limbe with sparse data to correlate. Some groundwater baseline hydrogeochemical studies have been carried out around Mount Cameroon [7-10]. The Limbe area is made up mostly pyroclastic and of jointed weathered fractured and columnar basalt resulting in volcanic fractured rock aquifers where saturated. In addition, Limbe being a coastal area in contact with the sea may experiences seawater intrusion.

From geophysical sections and bore well drill cuttings, the litho-stratigraphy is sub-divided into three layers as in figure 3; a soil cover formation topmost which constitutes weathered rocks, recent degradation of lava flows, transported materials, black soils and volcanic sands. This formation has a smaller volume as compared to the underlying basalts and has received only minor alterations by tectonic activities. The intermediate layer is made up of younger fractured columnar basalts and volcanic sand that constitute the aquifer. The basaltic rocks show traces of grinding, crushing, fracturing in a SW-NE direction, these fractures are the major fractures determining the storage of groundwater in the aquifers in the basal to-andesitic formation. The Ancient massive basalts bottom Formation make up the oldest formation and these rocks are the oldest in age. This formation has no fractures and as such do not contain water.

Materials and Methods

Materials

The field materials and equipment used in the study are listed in table 1; they were calibrated as per manufacturer's specifications.

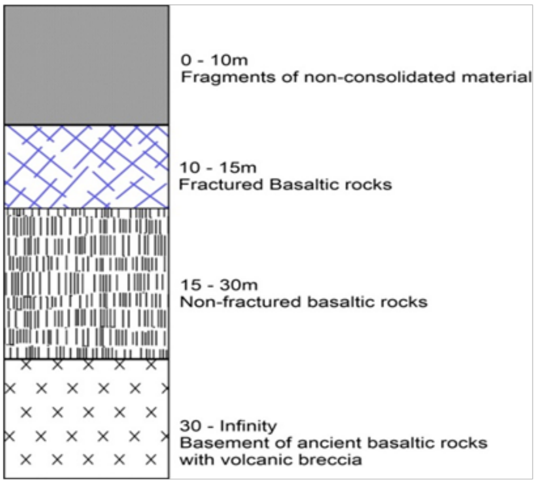

Figure 3: Geophysical section of formations in, Limbe

Equipment/Softwares	Specifications	Functions
Bike	Commercial bikes (Bensikin)	To transport fieldworkers to wells
GPS	GARMIN GPSMAP 60CSx	To measure longitude, latitude and elevation of wells
EC Meter	HANNA HI 98304/ HI98303	To measure Electrical Conductivity of water.
pH Meter	HANNA HI 98127/ HI98107	To measure pH of water.
Water level indicator	Solinst Model 102M	To indicate static water levels of water in wells
Measuring Tape	Weighted measuring tape	Measurement of well diameter and depth.
Digital Thermometer	Extech 39240 (-50 to 200°C)	To measure temperature of water
Total Dissolved Solid meter	Hanna HI 96301 with ATC	To measure Total dissolved solids in water
Water sampler	Gallenkampf 1000ml	To collect well water sample from well
Sample bottles	Polystyrene 500ml	To hold sample for onward transmission to laboratory
ArcGIS	Version 10.1	GIS Drawing sampling/Tests location maps
Global Mapper	Version 15	GIS Geolocation of wells
Surfer Golden Software	Version 12	GIS plotting contours for spatial distribution
AqQA/ Aquachem	Version 15	For the analysis/interpretation of water chemistry

Table 1: Field Equipment, Software's, their specifications and functions.

Methods

An extensive field program of bore well; data acquisition, field hydrogeological measurement/tests, sampling and laboratory analysis of collected water was conducted in Limbe according to protocols; ISO 5667 1 [11], ISO 5667-11 [12], ISO 5667-3 [13] and Barcelona et al., [14].

A field visit was done in August 2016 by with hydrogeological traverse field mapping to determine appropriate hand-dug wells, boreholes, springs and streams. Field measurements and sampling started from Moliwethrough to Down Beach. The city of Limbe was divided into zones and work was carried out in two seasons; wet season September 2016 and dry season February 2017. GIS platforms were used to analyze field data for the creation of sample location, drainage and water level contour maps.

Measurements were carried out for longitudes, latitudes, Surface elevation, Wells: Well water level and Well depths Groundwater tests were carried out as follows: 897 in situ tests were carried out in 154 wells (147 hand dug wells and 7 boreholes) for Temperature (°C), pH, Electrical Conductivity (EC) and Total Dissolved Solids (TDS). Nine9 selected wells went dry during dry season. Forty 40 groundwater samples were collected; 20 samples 13 hand-dug wells, 5 boreholes, 1 river and 1 spring for each season. Samples were collected in 500ml containers, sealed and sent to Institute of Agricultural Research and Development-I.R.A.Dusing the standard methods APHA [15] to analyze for:

- Major cations in mg/L: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and NH_4^{+}.
- Major anions in mg/L: HCO_3^{-}, Cl^{-} , SO_4^{2-}, $HPO_4^{2-}$and NO_3^{-}.

To fully understand the relationship between the geology of the area, groundwater, hydrogeochemical tools were used such as:

Ionic ratio for indicative elements is a useful hydrogeochemical tool to identify source rock of ions and formation contribution to solute hydrogeochemistry [16].These were used in this study.

Gibbs Diagram is a plot of Na^{+}/ (Na^{+}+HCO_3^{-} Ca^{2+}) and Cl^{-}/ (Cl+HCO_3^{-}) as a function of TDS are widely employed to determine the sources of dissolved geochemical constituents. These plots reveal the relationships between water composition and the three main hydrogeochemical processes involved in ions acquisition; Atmospheric precipitation, rock weathering or evaporation crystallisation.

Pipers Diagram is a graphical representation of the chemistry of water sample on three fields; the cation ternary field with Ca, Mg and Na+K apices , the anion ternary field with HCO_3, SO_4 and Cl^{-} apices. These two fields are projected onto a third diamond field. The diamond field is a matrix transformation of the graph of the anions [sulphate chloride]/Σ anions and cations [Na+K]/Σ cations. This plot is a useful hydrogeochemical tool to compare water samples, determine water type and hydrogeochemical facies Langguth [17]. This has been used here for these purposes.

Durov diagram is a composite plot consisting of two ternary diagrams where the mill equivalent percentages of cations are plotted perpendicularly against those of anions; the sides of the triangles form a central rectangular binary plot of total cation vs. total anion concentrations. These are divided into nine classes by Lloyd and Heathcoat [18] which give the hydrogeochemical processes determining the character of the water types in the aquiferous formation Langguth [17].

WQI was calculated by adopting Weighted Arithmetical Index method considering thirteen water quality parameters (pH, EC, TDS, total alkalinity, total hardness, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, NH_4^{+}) in order to assess the degree of groundwater contamination and suitability listed in table 2.

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For Agro-industrial suitability the following parameters were used; sodium adsorption ratio SAR, permeability index PI, Magnesium adsorption ratio MAR, percent sodium %Na, Kelly's ratio KR and Residual sodium carbonate RSC and Wilcox diagram listed in table 2.

The following software's; Surfer 12, Global mapped 11 and AqQA 1.5 AGIS 10.3 were used for data presentation, interpretation and analysis.

Indices	Formula	Reference
Percentage Sodium	$\%Na = \frac{Na^{+} + K^{+}}{Na^{+} + K^{+} + Ca^{2+} + Mg^{2+}} \times 100$	Wilcox [19]
Kelly Ratio	$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}}$	Kelly [20]
Magnesium Absorption Ratio	$MAR = \left(\frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}}\right) \times 100$	Szaboles and Barab [21]
Total Hardness	TH ($CaCO_3$) mg/L = 2.5 Ca^{2+} + 4.1Mg^{2+}	Todd [22]
Residual Sodium Carbonate	$RSC = (CO_3 + HCO_3 - (Ca + Mg))$	Eaton and Ragunath [23,24]
Sodium Absorption Ratio	$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$	Richard [25]
Permeability Index	$PI = \frac{((Na + K) + \sqrt{HCO_3}) * 100}{Ca + Mg + Na + K}$	Doneen [26]
Water Quality Index	$WQI = \sum_{i=1}^{n} W_i q_i \left[\sum_{i=1}^{n} W_i\right]^{-1}$	Sisodia and Moundiotiya, [27]

Table 2: Formulae for the determination for indices/parameters for water quality assessment.

Results and Interpretation

Physicochemical parameters

The field measured physicochemical parameters of groundwater in Limbe are: Temperature, pH, EC and TDS for selected wells in each quarter shown in table 3.The summary statistics for all 154 tested wells in Limbe is shown in table 4. The EC values (WEC; DEC) increase with decrease in the Distance to Shoreline (DS) in both seasons. Wet season ECs (WEC) are lower than dry season ECs (DEC) as in figure 4.

The wells are at surface elevations of 1m to 245m with well-depths ranging from 1.8 to 6.2m and at distances from shoreline of 46.67 to 5223.53m.

Surface elevation: Surface elevations range from -2m.a.m.s.l at lower Motowoh to 256 a.m.s.l at Mile 4 shown in figure 5. Limbe is low lying on the shorelines of the Atlantic Ocean at the foot hills of Mount Cameroon. The low elevation areas are prone to floods in the rainy season.

Well parameters: The wells have depths ranging from 0.75m at Church Street to 13.17m at Upper Mawoh for hand-dug wells and from 36m at Sokolo (Bota New layout) to 62m at Lake Restaurant (Sokolo old road) for boreholes, depth to water levels ranged from 0.22m at Church Street to 8.17m at upper Mawohfor hand-dug wells and 20m at Lake Restaurant to 40m at Karrata shown in figure 6.

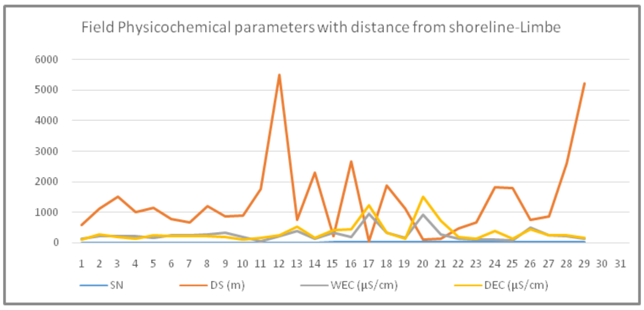

Figure 4: Seasonal variations in field measured groundwater electrical conductivities with distance from shoreline in Limbe: The EC values (WEC; DEC) increase with decrease in the distance to shoreline (DS) in both seasons. Wet season ECs (WEC) are lower than dry season ECs (DEC).

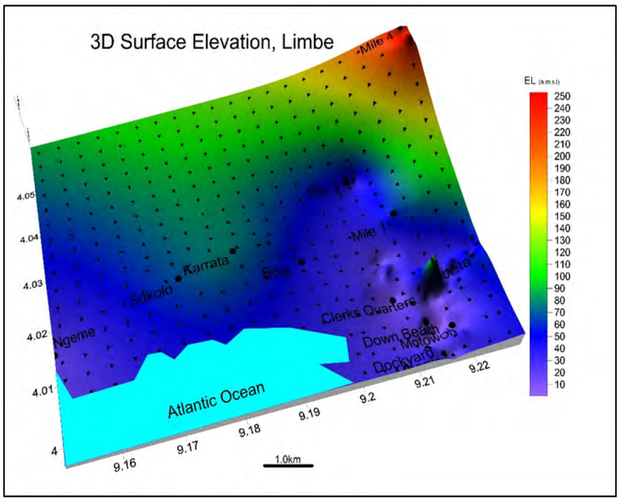

Figure 5: Surface elevation profile of Limbe. Areas of low elevations are Church Street, Clerks Quarters, Mabeta, Kulu, Dockyard and highest elevation area is Mile 4. This elevation depicts discharge into the ocean.

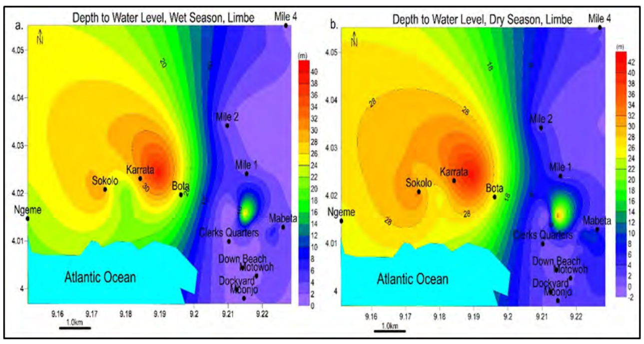

Figure 6: Groundwater level contours for (a) wet season and (b) dry season; with least value at Church Street (0.22m) and highest value at Karrata (40m) in both seasons. Groundwater can be found at shallow levels like Church unlike Karrata.

SN	Location	E	N	SE (m)	DS(m)	WD (m)	WSL(m)	WT (^{0}C)	WpH	WEC (µS)	WTDS (mg/L)	DSL (m)	DT (0C)	DpH	DEC (µS)	DTDS (mg/L)
1	Motowoh	9.2183	4.0027	9	574.59	2.68	1.64	27.2	7.6	119	79.73	1.86	28.3	6.7	130	87.1
2	New Town	9.2146	4.0158	29	1113.61	42	25	27.2	7.8	208	139.36	29	26.2	6.9	295	197.65
3	Karrata 2	9.1896	4.0242	70	1511.49	62	40	26.2	7.9	217	145.39	45	28.7	6.9	212	142.04
4	Sokolo	9.1739	4.0208	109	1011.36	36	25	25.7	8	225	150.75	30	28.5	6.9	144	96.48
5	Mawoh	9.2207	4.0093	32	1144.73	5.83	3.11	27.1	6.3	162	108.54	3.45	28.7	6.6	248	166.16
6	Clerks Qters	9.2102	4.0099	4	776.86	2.45	1.5	25.1	8.2	245	164.15	2.25	27.8	6.9	227	152.09
7	Ngeme	9.1512	4.0147	34	669.06	45	16	25.6	7.8	238	159.46	20	25.8	7	224	150.08
8	Karrata	9.1842	4.0231	77	1200.3	55	30	25.6	8	282	188.94	30	27.1	6.9	231	154.77
9	Church Str.	9.2096	4.0164	30	861.33	2.69	1.79	27	7.4	334	223.78	2.18	28	6.9	217	145.39
10	Mbonjo	9.2146	3.998	30	900.23	1.86	1	26.6	7.6	180	120.6	0.71	27.8	6.9	121	81.07
11	Mabeta	9.2261	4.0129	39	1778.22	7.59	2	26.3	7.2	46	30.82	5.6	30.4	7	166	111.22
12	Mile 4	9.2269	4.0552	240	5512.49	2.73	1.64	25.5	8	221	148.07	2.19	27.5	6.7	259	173.53
13	Westend	9.2165	4.0092	18	742.41	3.59	1	26.9	7.7	378	253.26	2.02	28.4	7.1	544	364.48
14	Mile 1-2	9.2205	4.0249	79	2311.69	2.85	1.93	26.1	8.5	138	92.46	2.37	27.5	6.8	187	125.29
15	Kulu	9.2142	4.0044	24	217.83	2.65	1.07	26.3	7.9	330	221.1	1.9	28.1	7.2	414	277.38
16	Mile 2	9.2097	4.0342	49	2674.45	2.86	1.6	25.4	7.2	196	131.32	1.6	27.8	7	452	302.84
17	Dockyard	9.2125	3.9998	1	46.57	2.82	1.17	27.1	7.7	963	645.21	1.85	28.8	7.2	1240	830.8
18	Mile 1	9.2154	4.0241	60	1889.36	3.83	3.45	26.3	8	335	224.45	3.75	27.3	6.8	334	223.78
19	Sokolo 2	9.1743	4.0213	81	1120.28	40	25	25.8	8.2	150	100.5	25	29	6.9	144	96.48
20	Dockyard 2	9.2126	3.9998	14	92.24	2.65	1	26.3	7.7	947	634.49	1.73	28.6	7	1515	1015.05
21	Kulu 2	9.2138	4.0029	8	124.36	2.89	1.04	26.8	8	284	190.28	1.79	28.6	7.3	742	497.14
22	Mbonjo 2	9.2152	3.9975	22	466.78	3.88	2.4	26.2	7.8	142	95.14	3.39	27.7	6.7	218	146.06
23	Motowoh 2	9.2186	4.0008	20	669.06	6.48	2.64	27.2	7.3	101	67.67	6.23	27.5	6.7	156	104.52
24	Mawoh 2	9.2251	4.0126	52	1811.56	11.38	3.74	26.5	7.2	98	65.66	11.17	27.3	6.8	404	270.68
25	Mabeta 2	9.2252	4.0131	37	1794.89	6.09	4.65	26.6	6.6	81	54.27	5.48	27.5	6.7	156	104.52
26	Westend 2	9.2163	4.0101	22	761.3	4.6	2.45	27.7	7.5	502	336.34	2.45	28.2	7.1	466	312.22
27	Church Str. 2	9.2091	4.0171	21	865.77	3.81	2	26.2	7.7	237	158.79	3.7	28	6.8	260	174.2
28	Mile 2-2	9.2108	4.0337	78	2622.88	4.34	4.16	26.1	7.1	226	151.42	4.16	27.1	7	254	170.18
29	Mile 4-2	9.2266	4.0522	245	5223.53	4.14	3.5	25.3	7.3	124	83.08	3.5	26.6	7	167	111.89

Table 3: Field measured physicochemical parameters of 29 representative wells during two seasons in Limbe.

Note: SN=Sample Number, WD=Well Depth, DS=Distance to Shoreline, WDW= Wet season Static water level, WT= Wet Season Temperature, WpH= Wet Season pH, WEC= Wet Season EC, WTDS=Wet Season TDS, DWL= Dry season Static water level, DT= Dry Season Temperature, DpH= Dry Season pH, DEC= Dry Season EC, DTDS= Dry Season TDS

Parameters	Wet				Dry			
	Min	Max	Mean	Std.	Min	Max	Mean	Std.
T(oC)	22.3	27.9	26.43	0.71	24.1	30.4	28.04	0.88
PH	6.1	8.5	7.28	0.51	6.4	7.8	6.84	0.23
EC (µS/cm)	38	963	213.87	160.35	59	1515	282.64	208.51
TDS (mg/L)	30.15	645.21	166.93	107.4	81.07	830.8	204.25	139.70

Table 4: Basic Statistics of the physicochemical tests for all 154 field tested wells in Limbe; min, max, mean and standard deviation of these parameters in two seasons.

Groundwater level contours: From elevation and depth to water level, the groundwater contours were drawn with equipotential vectors simulating groundwater flow lines and flow direction presented in figure 7. Groundwater levels mimic the surface topography from high areas Mile 4 to low areas Church Street, Mbonjo. The groundwater flows into the Atlantic Ocean.

Temperature: The temperature values ranged from 22.3 - 27.9°C in the wet season and 24.1 - 30.4°C in the dry season seen in figure 8. The temperatures of groundwater in Limbe and environs are relatively low. There is a general increase from wet to dry season.

pH: pH values ranged from slightly to alkaline 6.1-8.5 in the wet season and slightly acidic to peralkaline 6.4-7.8 in the dry season as in figure 9.

Electrical Conductivity (EC): The values ranged between 38-963 µS/cm in wet season and 59-1515 µS/cm in the dry season shown in figure 10. The higher values of electrical conductivity are due to high solute concentration in water.

Total dissolved solids: TDS ranged from 25.46 to 645.21 mg/L in the wet season and 39.53 to 830.8 mg/L in the dry season seen in figure 11. This indicates a freshwater area except for Dockyard.

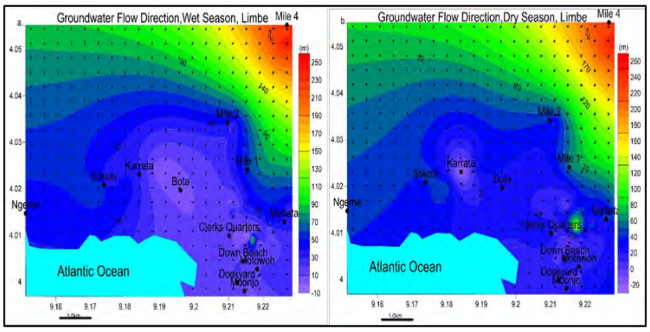

Figure 7: Spatial variation of Flow direction for (a) wet season and (b) dry season. Note: water moves away from peak values area (Mile 4) and moves towards lower value areas (Church Street, Clerk quarters, Mabeta, Dockyard) and into the ocean.

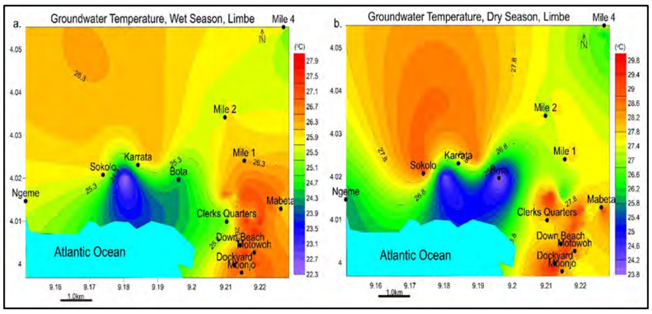

Figure 8: Spatial variation of Temperature values for both a) wet and b) dry seasons. There is an increase from wet to dry season. The lowest values come from areas along the Atlantic Ocean. Highest values are found in the North, Northwest a1nd Southeast of Limbe.

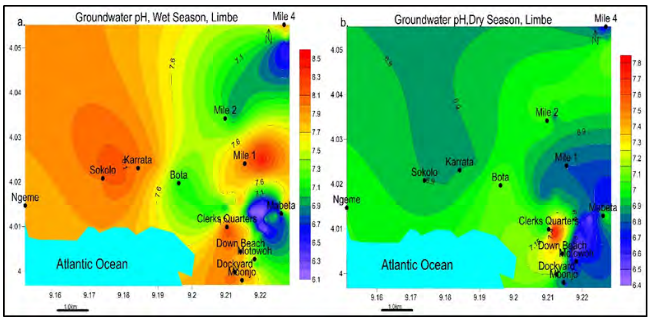

Figure 9: Spatial variation of pH values for a) wet and b) dry seasons. Highest values are found North, Northwest through South in the wet season and Southeast in the dry season. Note: pH values are more elevated in the wet season than dry season.

Chemical properties of groundwater

The results of the chemical analysis varied in both seasons. In the wet season $Ca^{+}>K^{+}>Mg^{2+}>Na^{+}>NH_4^{+}$- $HCO_3>Cl^{-}>HPO_4^{2-}>SO_4^{2-}>NO_3^{-}$ and $Ca^{+}>K^{+}>Mg^{2+}>Na^{+}$- $HCO_3>Cl^{-}>SO_4^{2-}>HPO_4^{2-}>NO_3^{-}$ dry season. Cl^{-} is widespread in the wet season than the dry season and peaks at Dockyard for both seasons. Most samples indicated a lack or decrease in Cl^{-} concentration in the dry season with the exception of Dockyard which experiences an increase in Cl^{-} concentrationspre- sented in tables 5, 6, and figures 12, 13.

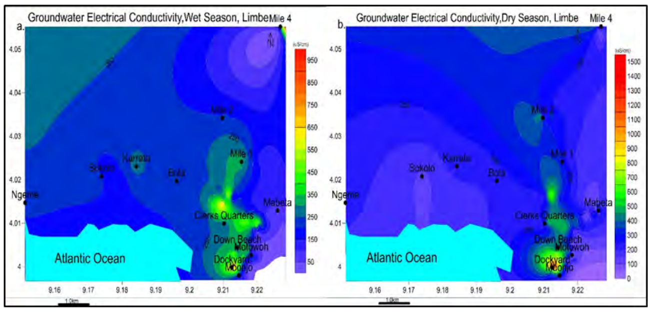

Figure 10: Spatial variation of Electrical Conductivity EC values for: a) wet and b) dry seasons. EC is maximum in the dry season and peaks Southeast of Limbe for both seasons. The highest value is 963 µS/cm in the wet season, and 1515 µS/cm in dry season, was recorded in Dockyard, Limbe.

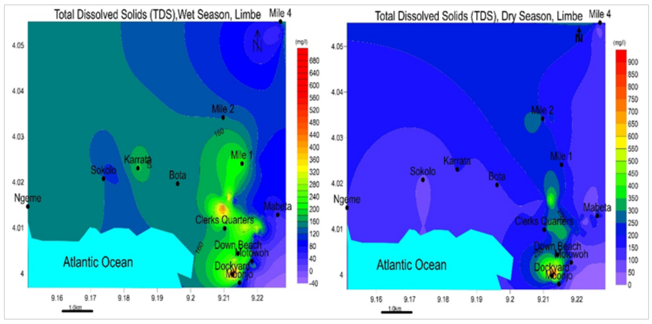

Figure 11: Spatial variation of Total Dissolved Solids for: a) wet and b) dry seasons. TDS is maximum in the dry season and peaks Southeast of Limbe for both seasons but the TDS shows a more distributed load of higher concentration in the wet season from Northwest to Southeast.

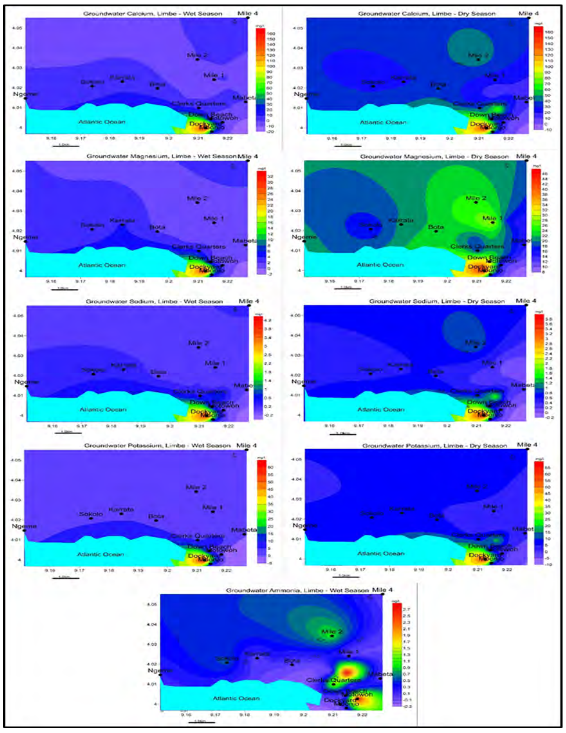

Figure 12: Spatial distribution of Cations a. Ca^{2+} b. Mg^{2+} c. Na^{+} c. K^{+} d. NH_4^{+} for Wet and dry seasons, Limbe

Wet (mg/L)											
SN	Names	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	HCO_3^-	NO_3^-	SO_4^{2-}	CL^-	HPO_4^{2-}
1	Motowoh	0.04	0.88	0.00	1.83	2.61	34.16	0.14	11.41	10.00	1.36
2	St Ann	0.04	0.88	0.00	1.53	2.88	142.74	0.66	8.09	8.00	2.29
3	Elegance	0.25	3.86	3.10	2.71	0.27	107.97	1.13	3.98	8.00	3.56
4	Sokolo	0.34	4.21	3.10	2.45	0.54	88.45	0.00	3.32	6.00	2.63
5	Mawoh	0.21	2.28	0.00	1.51	0.18	18.91	0.00	5.43	22.00	1.70
6	Clerks Quarters	0.39	4.39	6.20	4.51	1.35	121.39	0.00	3.13	8.00	1.52
7	Limbe River	0.3	3.51	3.10	2.99	0.00	127.49	0.00	2.67	6.00	2.89
8	Ngeme	0.26	3.16	3.10	3.11	0.18	116.51	0.00	2.2	6.00	3.23
9	Karrata	0.30	3.86	6.20	4.22	0.00	101.87	0.43	2.25	7.00	23.87
10	Church Street	0.21	1.93	0.00	1.23	0.00	99.43	0.63	4.63	25.00	2.63
11	Mbonjo	0.30	2.46	0.00	2.1	0.00	83.57	2.58	3.6	10.00	6.11
12	Mabeta	0.00	0.53	0.00	1.76	0.00	0.61	0.02	3.32	10.00	0.08
13	Mile 4	0.26	2.81	3.10	2.67	0.00	48.19	0.00	5.33	18.00	0.00
14	Westend	0.86	10.00	2.79	1.46	0.00	100.65	0.00	10.66	32.00	0.00
15	Towe	0.09	1.05	0.00	1.63	0.00	57.95	0.00	3.23	9.00	0.00
16	Kulu	0.30	3.69	3.1	2.71	0.00	165.31	0.00	6.03	23.00	9.85
17	Mile 2	0.09	1.76	0.00	1.61	0.99	71.37	0.00	3.65	14.00	0.00
18	Dockyard	4.11	60.37	161.2	31.45	0.00	173.45	0.00	16.14	77.00	5.95
19	Spring	0.13	2.98	3.00	1.90	0.00	112.85	0.08	2.11	5.00	0.60
20	Rain	0.00	0.70	0.00	1.65	0.00	0.00	0.00	4.91	8.00	0.00
	Min	*0.00*	*0.53*	*0.00*	*1.23*	*0.00*	*0.00*	*0.00*	*2.11*	*5.00*	*0.00*
	Max	*4.11*	*60.37*	*161.20*	*31.45*	*2.88*	*173.45*	*2.58*	*16.14*	*77.00*	*23.87*
	Mean	*0.42*	*5.77*	*9.90*	*3.75*	*0.45*	*88.64*	*0.28*	*5.30*	*15.60*	*3.41*
	Std	*0.89*	*13.02*	*35.67*	*6.58*	*0.87*	*49.78*	*0.62*	*3.65*	*16.32*	*5.45*

Table 5: Basic statistics of results from chemical Analysis of groundwater for wet season, Limbe. The values of rainwater, springs, streams, Rivers and groundwater are similar indicating connectivity typical of phreatic aquifers in fractured rock aquifers.

Dry (mg/L)											
SN	Names	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	HCO_3^-	NO_3^-	SO_4^{2-}	CL^-	HPO_4^{2-}
1	Motowoh	0.30	1.6	14.00	13.78	0.00	41.48	0.00	2.31	2.00	0.12
2	St Ann	0.25	1.25	14.00	22.16	0.00	103.70	0.00	0.60	0.00	0.41
3	Elegance	0.62	6.28	32.40	20.82	0.00	124.44	0.01	0.00	0.00	0.20
4	Sokolo	0.55	5.85	27.80	16.26	0.00	76.86	0.00	0.00	0.00	0.20
5	Mawoh	0.3	4.29	23.20	18.85	0.00	84.18	0.01	0.00	9.00	0.24
6	Clerks Quarters	0.74	7.53	37.20	18.14	0.00	136.64	0.00	1.86	0.00	0.14
7	Limbe River	0.58	6.28	32.40	21.76	0.00	135.42	0.00	0.15	0.00	0.16
8	Ngeme	0.58	5.46	32.40	20.93	0.00	123.22	0.00	0.91	0.00	0.16
9	Karrata	0.55	6.28	27.80	20.71	0.00	115.90	0.01	0.15	0.00	0.12
10	Church Street	0.37	2.5	23.20	18.85	0.00	109.80	0.00	1.66	25.00	0.20
11	Mbonjo	0.32	2.33	18.60	14.5	0.00	43.92	0.00	1.11	0.00	0.10
12	Mabeta	0.25	1.25	14.00	14.5	0.00	18.30	0.00	1.86	3.00	0.24
13	Mile 4	0.64	5.85	32.40	19.48	0.00	101.26	0.01	0.91	8.00	0.08
14	Westend	1.59	18.72	74.20	21.96	0.00	153.72	0.00	10.06	17.00	0.39
15	Towe	0.07	1.99	23.20	16.56	0.00	87.84	0.01	0.91	0.00	0.31
16	Kulu	0.62	5.03	32.40	31.92	0.00	208.62	0.00	3.12	9.00	0.31
17	Mile 2	0.94	7.89	46.40	24.96	0.00	145.18	0.00	5.68	10.00	0.61
18	Dockyard	3.77	62.74	155.20	44.54	0.00	602.68	0.00	16.8	67.00	0.12
19	Spring	0.58	5.58	37.20	23.3	0.00	125.66	0.00	0.60	0.00	0.20
20	Alpha Club	0.37	1.79	23.20	29.16	0.00	163.48	0.00	0.20	6.00	0.18
	Min	*0.07*	*1.25*	*14.00*	*13.78*	*0.00*	*18.30*	*0.00*	*0.00*	*0.00*	*0.08*
	Max	*3.77*	*62.74*	*155.20*	*44.54*	*0.00*	*602.68*	*0.01*	*16.80*	*67.00*	*0.61*
	Mean	*0.70*	*8.02*	*36.06*	*21.66*	*0.00*	*135.12*	*0.00*	*2.44*	*7.80*	*0.22*
	Std	*0.79*	*13.44*	*31.11*	*7.09*	*0.00*	*118.70*	*0.00*	*4.14*	*15.49*	*0.13*

Table 6: Basic statistics of results from chemical Analysis of groundwater for dry season, Limbe.The values of rainwater, springs, streams, Rivers and groundwater are similar indicating connectivity typical of phreatic aquifers in fractured rock aquifers.

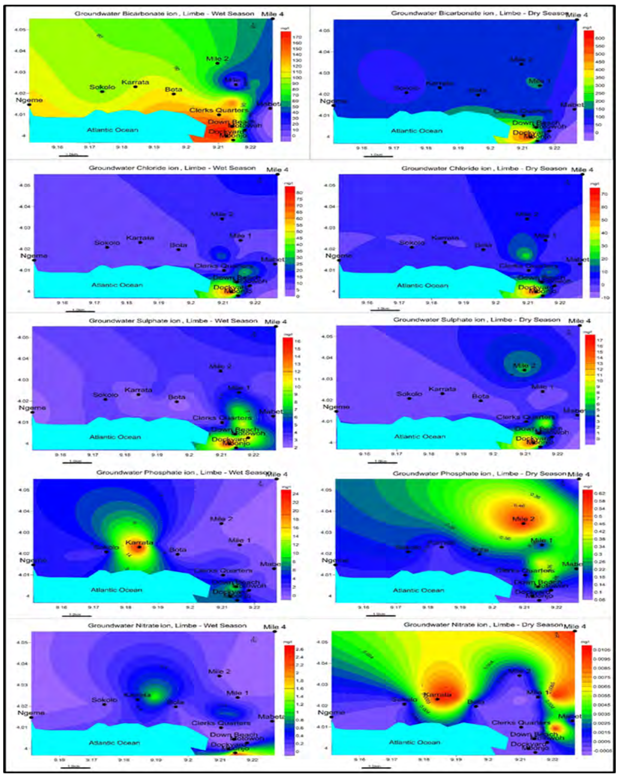

Figure 13: Spatial distribution of Anions a. HCO_3^- b. CL^- c. SO_4^{2-} c. HPO_4^{2-} d. NO_3^- for Wet and Dry seasons, Limbe.

Mechanisms controlling water chemistry

Ionic Ratios of Groundwater: 18 ionic ratios in groundwater were used to deduce formation inputs in the coastal town of Limbe, as presented in tables 7, 8 and 9.

12 of the 18, 66.7% ionic ratios calculated gave indices indicating silicate weathering of geologic formations in Limbe as a source of solute concentration in the groundwater while nitrate ratio indicates no anthropogenic contribution and sulfate indices indicates no oxidation of sulfides. Sulphate and Sodium indices indicate alternative sources of ions such as silicate weathering and ion exchange. Ca and Mg are sourced from silicate weathering. Sodium, Chloride and Bicarbonate indices indicate seawater intrusion; this is prominent in Dockyard and to some extent in Church Street, Mabeta, Mawoh, Motowoh, West End and Mbonjo. There is no plagioclase weathering, gypsum dissolution nor dolomitization.

Rock-Groundwater Interaction in Limbe: From Gibbs diagram for cations; 20 samples 100% are of rock-weathering dominance and for anions; 18 samples 90% are of rock weathering dominance and 2 samples 10% are of the atmospheric precipitation dominance during the wet season. During the dry season for cations and anions, all 20 samples 100% are controlled by rock weathering as in figure 14 and table 10. This reveals the weathering of the aquifer matrix as the primary dominant process in the acquisition of ions and atmospheric precipitation as the secondary process controlling the hydrogeochemistry in Limbe.

No	SO_4/ Cl	Na/ Cl	Mg/Cl	Na/ HCO_3	Ca/ HCO_3	Ca/ SO_4	Ca/ Mg	Ca+Mg/ Na+K	HCO_3 /∑An	NO_3/ ∑An	SO_4/ ∑An	Cl/ ∑An	Na^+K^-Cl /Na^+ K^-Cl^+Ca	Na /Na^+Cl	Mg /Ca^+Mg	Ca /Ca^+SO_4	Ca^+Mg /SO^4	Mg/ Ca
1	1.16	0.15	6.89	0.01	0.34	6.06	1.02	14.62	0.90	0.00	0.05	0.04	-0.01	0.13	0.50	0.86	12.03	0.98
2	0.00	0.00	0.00	0.00	0.14	23.33	0.63	24.11	0.99	0.00	0.01	0.00	0.10	1.00	0.61	0.96	60.27	1.58
3	0.00	0.00	0.00	0.00	0.26	0.00	1.56	7.71	1.00	0.00	0.00	0.00	0.18	1.00	0.39	1.00	0.00	0.64
4	0.00	0.00	0.00	0.01	0.36	0.00	1.71	6.88	1.00	0.00	0.00	0.00	0.19	1.00	0.37	1.00	0.00	0.58
5	0.00	0.03	2.09	0.00	0.28	0.00	1.23	9.16	0.90	0.00	0.00	0.10	-0.23	0.03	0.45	1.00	0.00	0.81
6	0.00	0.00	0.00	0.01	0.27	20.00	2.05	6.69	0.99	0.00	0.01	0.00	0.18	1.00	0.33	0.95	29.75	0.49
7	0.00	0.00	0.00	0.00	0.24	216.00	1.49	7.90	1.00	0.00	0.00	0.00	0.17	1.00	0.40	1.00	361.07	0.67
8	0.00	0.00	0.00	0.00	0.26	35.60	1.55	8.83	0.99	0.00	0.01	0.00	0.16	1.00	0.39	0.97	58.60	0.65
9	0.00	0.00	0.00	0.00	0.24	185.33	1.34	7.10	1.00	0.00	0.00	0.00	0.20	1.00	0.43	0.99	323.40	0.74
10	0.07	0.01	0.75	0.00	0.21	13.98	1.23	14.65	0.80	0.00	0.01	0.18	-20.68	0.01	0.45	0.93	25.33	0.81
11	0.00	0.00	0.00	0.01	0.42	16.76	1.28	12.49	0.97	0.00	0.02	0.00	0.12	1.00	0.44	0.94	29.82	0.78
12	0.62	0.08	4.83	0.01	0.77	7.53	0.97	19.00	0.78	0.00	0.08	0.13	-0.12	0.08	0.51	0.88	15.32	1.04
13	0.11	0.08	2.44	0.01	0.32	35.60	1.66	7.99	0.92	0.00	0.01	0.07	-0.05	0.07	0.38	0.97	57.01	0.60
14	0.59	0.09	1.29	0.01	0.48	7.38	3.38	4.73	0.85	0.00	0.06	0.09	0.04	0.09	0.23	0.88	9.56	0.30
15	0.00	0.00	0.00	0.00	0.26	25.49	1.40	19.30	0.99	0.00	0.01	0.00	0.08	1.00	0.42	0.96	43.69	0.71
16	0.35	0.07	3.55	0.00	0.16	10.38	1.02	11.38	0.94	0.00	0.01	0.04	-0.12	0.06	0.50	0.91	20.62	0.99
17	0.57	0.09	2.50	0.01	0.32	8.17	1.86	8.08	0.90	0.00	0.04	0.06	-0.03	0.09	0.35	0.89	12.56	0.54
18	0.25	0.06	0.66	0.01	0.26	9.24	3.48	3.00	0.88	0.00	0.02	0.10	0.00	0.05	0.22	0.90	11.89	0.29
19	0.00	0.00	0.00	0.00	0.30	62.00	1.60	9.82	0.99	0.00	0.00	0.00	0.14	1.00	0.39	0.98	100.83	0.63
20	0.03	0.06	4.86	0.00	0.14	116.00	0.80	24.24	0.96	0.00	0.00	0.04	-0.20	0.06	0.56	0.99	261.80	1.26
Min	*0.00*	*0.00*	*0.00*	*0.00*	*0.14*	*0.00*	*0.63*	*3.00*	*0.78*	*0.00*	*0.00*	*0.00*	*-20.68*	*0.01*	*0.22*	*0.86*	*0.00*	*0.29*
Max	*1.16*	*0.15*	*6.89*	*0.01*	*0.77*	*216.00*	*3.48*	*24.24*	*1.00*	*0.00*	*0.08*	*0.18*	*0.20*	*1.00*	*0.61*	*1.00*	*361.07*	*1.58*
Mean	*0.19*	*0.04*	*1.49*	*0.01*	*0.30*	*39.94*	*1.56*	*11.39*	*0.94*	*0.00*	*0.02*	*0.04*	*-0.99*	*0.53*	*0.41*	*0.95*	*71.68*	*0.75*
Std	*0.32*	*0.05*	*2.07*	*0.00*	*0.14*	*61.31*	*0.73*	*6.10*	*0.07*	*0.00*	*0.02*	*0.05*	*4.64*	*0.48*	*0.10*	*0.05*	*109.24*	*0.31*

Table 7: Ionic ratios of groundwater ions: Summary statistics for wet season.

Citation: Akoachere RA, Egbe SE, Eyong TA, Yaya OO, Mbua RL, et al. (2019) Characterization of Groundwater in the Basaltic Fractured Rock Aquiferous Formations of the Limbe Coastal Region of Mount Cameroon, SWR-Cameroon. J Environ Sci Curr Res: S1002.

No	SO_4/ Cl	Na/ Cl	Mg/Cl	Na/ HCO_3	Ca/ HCO_3	Ca/ SO_4	Ca/ Mg	Ca+Mg/ Na+K	HCO_3 /∑An	NO_3/ ∑An	SO_4/ ∑An	Cl/ ∑An	Na^+K^+Cl /Na^+ K^-Cl^+Ca	Na /Na^+Cl	Mg /Ca^+Mg	Ca /Ca^+SO_4	Ca^+Mg /SO^4	Mg/ Ca
1	1.16	0.15	6.89	0.01	0.34	6.06	1.02	14.62	0.90	0.00	0.05	0.04	-0.01	0.13	0.50	0.86	12.03	0.98
2	0.00	0.00	0.00	0.00	0.14	23.33	0.63	24.11	0.99	0.00	0.01	0.00	0.10	1.00	0.61	0.96	60.27	1.58
3	0.00	0.00	0.00	0.00	0.26	0.00	1.56	7.71	1.00	0.00	0.00	0.00	0.18	1.00	0.39	1.00	0.00	0.64
4	0.00	0.00	0.00	0.01	0.36	0.00	1.71	6.88	1.00	0.00	0.00	0.00	0.19	1.00	0.37	1.00	0.00	0.58
5	0.00	0.03	2.09	0.00	0.28	0.00	1.23	9.16	0.90	0.00	0.00	0.10	-0.23	0.03	0.45	1.00	0.00	0.81
6	0.00	0.00	0.00	0.01	0.27	20.00	2.05	6.69	0.99	0.00	0.01	0.00	0.18	1.00	0.33	0.95	29.75	0.49
7	0.00	0.00	0.00	0.00	0.24	216.00	1.49	7.90	1.00	0.00	0.00	0.00	0.17	1.00	0.40	1.00	361.07	0.67
8	0.00	0.00	0.00	0.00	0.26	35.60	1.55	8.83	0.99	0.00	0.01	0.00	0.16	1.00	0.39	0.97	58.60	0.65
9	0.00	0.00	0.00	0.00	0.24	185.33	1.34	7.10	1.00	0.00	0.00	0.00	0.20	1.00	0.43	0.99	323.40	0.74
10	0.07	0.01	0.75	0.00	0.21	13.98	1.23	14.65	0.80	0.00	0.01	0.18	-20.68	0.01	0.45	0.93	25.33	0.81
11	0.00	0.00	0.00	0.01	0.42	16.76	1.28	12.49	0.97	0.00	0.02	0.00	0.12	1.00	0.44	0.94	29.82	0.78
12	0.62	0.08	4.83	0.01	0.77	7.53	0.97	19.00	0.78	0.00	0.08	0.13	-0.12	0.08	0.51	0.88	15.32	1.04
13	0.11	0.08	2.44	0.01	0.32	35.60	1.66	7.99	0.92	0.00	0.01	0.07	-0.05	0.07	0.38	0.97	57.01	0.60
14	0.59	0.09	1.29	0.01	0.48	7.38	3.38	4.73	0.85	0.00	0.06	0.09	0.04	0.09	0.23	0.88	9.56	0.30
15	0.00	0.00	0.00	0.00	0.26	25.49	1.40	19.30	0.99	0.00	0.01	0.00	0.08	1.00	0.42	0.96	43.69	0.71
16	0.35	0.07	3.55	0.00	0.16	10.38	1.02	11.38	0.94	0.00	0.01	0.04	-0.12	0.06	0.50	0.91	20.62	0.99
17	0.57	0.09	2.50	0.01	0.32	8.17	1.86	8.08	0.90	0.00	0.04	0.06	-0.03	0.09	0.35	0.89	12.56	0.54
18	0.25	0.06	0.66	0.01	0.26	9.24	3.48	3.00	0.88	0.00	0.02	0.10	0.00	0.05	0.22	0.90	11.89	0.29
19	0.00	0.00	0.00	0.00	0.30	62.00	1.60	9.82	0.99	0.00	0.00	0.00	0.14	1.00	0.39	0.98	100.83	0.63
20	0.03	0.06	4.86	0.00	0.14	116.00	0.80	24.24	0.96	0.00	0.00	0.04	-0.20	0.06	0.56	0.99	261.80	1.26
Min	*0.00*	*0.00*	*0.00*	*0.00*	*0.14*	*0.00*	*0.63*	*3.00*	*0.78*	*0.00*	*0.00*	*0.00*	*-20.68*	*0.01*	*0.22*	*0.86*	*0.00*	*0.29*
Max	*1.16*	*0.15*	*6.89*	*0.01*	*0.77*	*216.00*	*3.48*	*24.24*	*1.00*	*0.00*	*0.08*	*0.18*	*0.20*	*1.00*	*0.61*	*1.00*	*361.07*	*1.58*
Mean	*0.19*	*0.04*	*1.49*	*0.01*	*0.30*	*39.94*	*1.56*	*11.39*	*0.94*	*0.00*	*0.02*	*0.04*	*-0.99*	*0.53*	*0.41*	*0.95*	*71.68*	*0.75*
Std	*0.32*	*0.05*	*2.07*	*0.00*	*0.14*	*61.31*	*0.73*	*6.10*	*0.07*	*0.00*	*0.02*	*0.05*	*4.64*	*0.48*	*0.10*	*0.05*	*109.24*	*0.31*

Table 8: Ionic ratios of groundwater ions: Summary statistics for dry season.

Ionic Ratio	Wet	Dry	Comments	Interpretation
SO_4/CL	0.19 - 1.14	0 - 1.16	Very High	Suggests additional sources of Sulphate.
Na/Cl	0 - 0.06	0 - 0.15	Low	Silicate weathering, some marine water.
Mg/Cl	0.05 - 0.6	0 - 6.89	Very High	Depict a silicate weathering environment
Na/HCO	0 - 0.02	0 - 0.01	Very Low	Low weathering of Na-silicates.
Ca/HCO	0 - 0.93	0.14 - 0.77	Low	Ca-silicate weathering from the basalts of Limbe.
Ca/SO_4	0 - 9.99	0 - 216	Very High	There is no gypsum dissolution in volcanic coastal regions
Ca/Mg	0 - 5.13	0.63 - 3.48	High	Typical of coastal regions due to cation-exchange
Mg/Ca	0 - 1	0.29 - 1.58	Very Low	Silicate rock weathering
(Ca+Mg)/(Na+K)	0.39 - 3.32	3 - 24.24	Very High	Occurrence of silicate weathering.
HCO_3^-/∑Anions	0 - 0.94	0.78 - 1	Low-High	Silicate weathering reactions and some seawater
NO_3/∑Anions	0 - 0.02	0 -(2.38E-05)	Low	No anthropogenicactivities.
SO_4/∑Anions	0.02 - 0.38	0 - 0.08	Low	No oxidation of sulphides.
Cl/∑Anions	0.04 -0.71	0 - 0.18	Low	Rock weathering
$\frac{Na^+ + K^+ - Cl^-}{Na^+ + K^+ - Cl^- + Ca^{2+}}$	-4.96-4.92	-20.68-0.20	Low-High	Plagioclase weathering unlikely
$\frac{Na^+}{Na^+ + Cl^-}$	0 - 0.05	0.01 - 1.0	Low-High	Some halite Solution; Reverse softening and seawater; Sodium source other than halite-albite, ion exchange
$\frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}}$	0.16 - 1.0	0.22 - 0.61	Low-High	Silicate weathering. Ferromagnesian minerals but no evidence of granitic weathering
$\frac{Ca^{2+}}{Ca^{2+} + SO_4^{2-}}$	0 - 0.91	0.86 - 1.0	Low-High	Ion exchange/Calcium removal and Calcium source from silicates
$\frac{Ca^{2+} + Mg^{2+}}{SO_4^{2-}}$	0.16-11.94	0 - 361.07	Low-High	No dolomite at all, Dedolomitization

Table 9: Interpretation of Ionic Ratios for wet and dry seasons with determined formation characteristics.

Rock-water Interaction	TDS mg/L	Wet				Dry			
		Cation	%	Anion	%	Cation	%	Anion	%
Rock - Weathering dominance	50-1000	20	100	18	90	20	100	20	100
Atmospheric Precipitation dominance	1-50	-	-	2	10	-		-	

Table 10: Wet and Dry seasonal variations in rock/groundwater interaction from Gibbs diagram, Limbe.

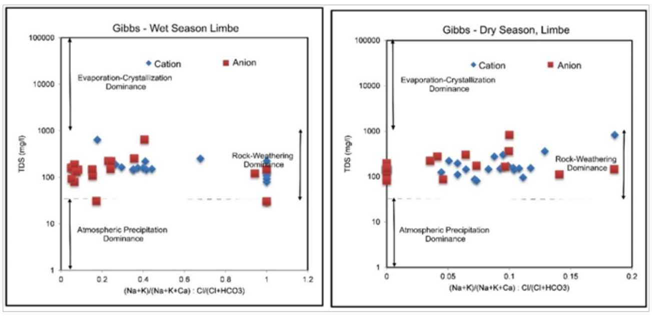

Figure 14: Gibbs Diagram indicating the interaction between aquifer formation and groundwater samples from Limbe. Almost all samples plot in the rock -weathering field for all the seasons.

Groundwater types: The diamond field of Piper's diagram was divided into seven classes A-G classifying water types and designated with alphabets from A to G are shown in figure 15. Using this Classification, water from Limbe is distinguished falls into A, B, C, D, E, G categories presented in table 11. There is no category F in the wet season and no B, C, D, E, F, and G in the dry. In the wet season: Category A; 5 samples, 25 %; characterized by normal earth alkaline water with prevailing bicarbonate. Category B; 3 samples, 15% are characterized by normal earth alkaline water with prevailing sulfate or chloride and Category C; 2 samples, 10 % are characterized by Normal earth alkaline water; prevailing chloride. Category D; 8 samples 40%; are characterized by earth alkaline water, with increased portions of alkalis and prevailing bicarbonate. Category E; 1 sample 5%; characterized by earth alkaline water, with increased portions of alkalis with prevailing chloride and Category G; 1 sample, characterized by alkaline water with prevailing bicarbonate. There are no categories B to G in the dry season and no Category F in the wet season. In the dry season: Category A; 20 samples, 100%. In the wet season, the dominant water types are Category A, 25%; and Category D, 40% while in the dry season Category A; 100%. From table 11, $MgHCO_3$ is the dominant water type, followed by CaCl, MgCl, Na + Clin the wet season and $MgHCO_3$ is the dominant water type, followed by $CaHCO_3$, in the dry season.

Piper's hydrogeochemical facies: From the Piper's diagram in figure14 the hydrogeochemical facies were determined and presented in table 12, Field (I): Ca-Mg-Cl-SO_4 hydrogeochemical facies has 3 samples, 15% in the wet and 0 samples and 0 % in the dry season. This facies is characteristic of stagnant at some distance along its flow path possibly from the slopes of Mount Cameroon. Field (III): Na-K-HCO_3 hydrogeochemical facies has 1 sample, 5% in the wet and 0 samples, 0 % in the dry season. This facies is characteristic of stagnant groundwater zones commonly zones of mixing in seawater encroached coastal regions. Field (IV), Ca-Mg-HCO_3 hydrogeochemical facies has 16 samples, 80% in the wet and 20 samples, 100% in the dry season. This facies is characteristic of freshly recharged groundwater that has equilibrated with CO_2 and soluble carbonate minerals under an open system conditions in the vadose zone typical of shallow groundwater flow systems in crystalline phreatic aquifers. No samples plotted on Field II in the wet season and Field II and III in the dry season. The high contribution of alkaline earth elements 80% in the wet season and 100 % in the dry season is due to direct ion-exchange processes which enrich groundwater with alkaline earth elements. The dominance of Ca-Mg-HCO_3 hydrogeochemical facies in this area could be due to dissolution of gases and minerals, particularly CO_2 and CO_2-related compounds from the atmosphere dissolved in precipitation and during groundwater infiltration through the vadose zone.

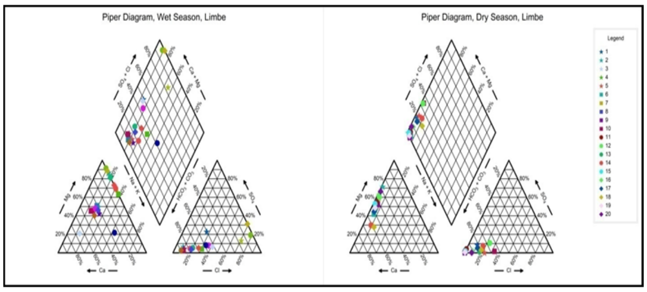

Figure 15: Piper's diagram for 3 water types and 3 groundwater hydrogeochemical facies in Limbe; in the wet season; Field (I): Ca-Mg-Cl-SO_4 has 3 samples 15%, Field III: Na- K-HCO_3 1 sample 5% and Field IV: Ca-Mg-HCO_3 has16 samples, 80%. In the dry season; Field (IV) Ca_Mg_$HCO_3$20 samples 100%. No samples plotted on Fields II in the wet or I and III in the dry season. Water types include; $MgHCO_3$ 90%; CaCl 5% and NaCl 5% in Wet seasons and $MgHCO_3$ 70%, $CaHCO_3$ (30%) dry season.

Hydrogeochemical character of Limbe groundwater: Based on the Durov's diagram, the classification by Lloyd and Heathcoat [18] presented in figure 16 for Limbe groundwater shows four classes occur in the wet season; Class-2; Ion exchange; 1 samples, 5%; Class-4 Recharge, 3 samples 15%; Class-5 Simple dissolution or mixing, 4 samples 20% and Class-6 Mixing and uncommon dissolution influences, 12 samples 60%. Three Classes occur in the dry season: Class-3 ion exchanged water, 10 samples, 50%; Class-5 Simple dissolution or mixing, 1 sample, 5% and Class-6 Mixing and uncommon dissolution influences, 9 samples 45% respectively. There are no Classes 1,3,7,8 and 9 in the wet season and no Classes 1, 2, 4, 7, 8 and 9 in the dry season in Limbe. In the wet season, fresh recently recharging water exchanges ions with the matrix of the formation, while simple dissolution or mixing also goes on between the recently recharging precipitation and the existing groundwater in the formation. In the dry season, recharging groundwater having spent more time in the formation continues to exchange ions to a lesser extent with the matrix of the formation while increasingly; simple dissolution or mixing also goes on between the recently recharging groundwater and the pre-existing groundwater in the formation, piston flow.

	Piper-Langguth Classification Limbe	Wet		Dry	
Class	Characteristic-Water type	No	%	No	%
	Diamond Field				
A	Normal earth alkaline water ; prevailing HCO_3^-	5	25	20	100
B	Normal earth alkaline water ; prevailing HCO_3^- or Cl^-	3	15	-	-
C	Normal earth alkaline water; prevailing Cl^-	2	10	-	-
D	Earth alkaline water ; increased portions of alkalis; prevailing HCO3-	8	40	-	-
E	Earth alkaline water with added portions of alkalis with prevailing chloride	1	5	-	-
G	Alkaline water with prevailing bicarbonate	1	5	-	-
	Cation Field				
1	Ca-rich waters	1	5	6	30
2	Mg-rich waters	18	90	14	70
3	Na+K	1	5	-	-
	Anion Field				
4	HCO_3^- waters	17	85	20	100
6	Cl^- waters	3	15	-	-

Table 11: Categories of Limbe groundwater.

Fields	Hydrogeochemical facies	Wet		Dry	
		No	%	No	%
Field I	Ca^{2+} - Mg^{2+} - Cl^- -SO_4^{2-}	3	15	-	-
Field III	Na^+ - K^+ - HCO_3^-	1	5	-	-
Field IV	Ca^{2+} - Mg^{2+} - HCO_3^-	16	80	20	100

Table 12: Classification of hydrogeochemical facies based on Piper diagram.

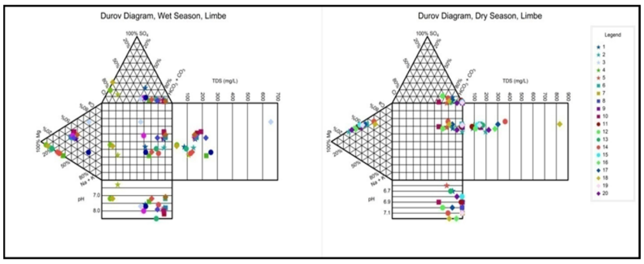

Figure 16: Durov plot of Limbe groundwater for the processes in groundwater evolution: for wet season; Field2, Ion exchange; 1 samples, 5%; Recharge, 3 samples 15%; Simple dissolution or mixing, 4 samples 20% and Mixing and uncommon dissolution influences, 12 samples 60% while in the dry season; ion exchange,1 sample, 50%; Simple dissolution or mixing, 1 samples, 5% and Mixing and uncommon dissolution influences, 9 samples 45%.

The presence of samples showing Na+ and Cl- as dominant cation /anion, Classes 2, 4, 5, 6 in the wet season and Classes 3, 5, 6 in the dry season, indicates that the groundwater in Limbe is related to ion exchange, simple dissolution and reverse or inverse ion exchange of NaCl waters or end-point down gradient waters such as seawater; indicative of seawater intrusion.

Rock-Groundwater interaction: Based on the Durov's diagram, the classification by Lloyd and Heathcoat [18] presented in table 13 shows that, in the wet season, most water samples plotted in Class 4, 5, 6, 95% and Class 5, 6, 50% in the dry season, which are water types not frequently encountered in basaltic terrains, but common in coastal regions; indicates probable mixing or uncommon dissolution influences with sulfate dominant or anion discriminate and Na dominant. In the dry season, 55% HCO_3 and Na are dominant, normally indicates ion exchanged water, although the generation of CO_2 at depth can produce HCO_3 where Na is dominant under certain circumstances; none is present in the wet season. In addition, few samples (20%, wet season and 5%, dry season) show No dominant anion or cation, indicating water exhibiting simple dissolution or mixing. 75% of the water in the wet season show SO_4 dominant, or anion discriminate, Ca, Nadominant; Ca and SO_4 dominant, frequently indicates recharge water in lava and gypsiferous deposits, otherwise mixed water or water exhibiting simple dissolution may be indicated; 5% in wet season and 50% in dry season showed water types dominated by Ca and HCO_3 ions with Na and HCO_3 ions respectively. Association with dolomite is presumed if Mg is significant. However, those samples in which Na is significant, an important ion exchanged is presumed. Durov diagram equally indicates simple dissolution of minerals during recharge and the dominant process governing rock-groundwater interaction as ion exchange in Limbe.

		Wet		Dry	
Class	Hydrogeochemical processes	No	%	No	%
2	This water type is dominated by Ca and HCO_3 ions. Samples in which Na is significant, an important ion exchange is presumed	1	5	-	-
3	HCO3 and Na are dominant, normally indicates ion exchanged water, although the generation of CO_2 at depth can produce HCO_3 where Na is dominant under certain circumstances	-	-	10	50
4	SO4 dominates, or anion discriminate and Ca dominant; mixed water or water exhibiting simple dissolution may be indicated.	3	15	-	-
5	No dominant anions or cations, indicates water exhibiting simple dissolution or mixing	4	20	1	5
6	SO4 dominant or anion discriminate and Na dominant; is water type that is not frequently encountered and indicates probable mixing or uncommon dissolution influences.	12	60	9	45

Table 13: Classification of Water based on Durov diagram 2 seasons.

Water Quality

Domestic water quality: Ionic content of water in the study area were evaluated using recommended values from WHO [28] guidlines. The quality standards for drinking water have been specified by the World Health Organization [28]. The suitability of groundwater in the study area based on WQI and total hardness HT are discussed below.

Water Quality Index (WQI): Permissible values of ions present in the groundwater have been used to calculate WQI values [29,30]. The weighted arithmetic water quality index was determined and presented in table 14.

In the wet and dry season, 50% to 55% of the groundwater samples fell in the category of excellent and 10-17.5% fell in the good water, while the few were poor and unsuitable for drinking and irrigation use. The spatial variation shows highest values at Dockyard in figure 17 for both seasons showing the water is unsuitable for both seasons.

		Wet		Dry	
Index	Quality	No	%	No	%
0-25	Excellent	10	50	11	55
26-50	Good	7	35	4	20
51-75	Poor	2	10	2	10
76-100	Very poor	-	-	1	5
>100	Unsuitable	1	5	2	10

Table 14: Water Quality Index Classification of groundwater samples for both wet and dry season.

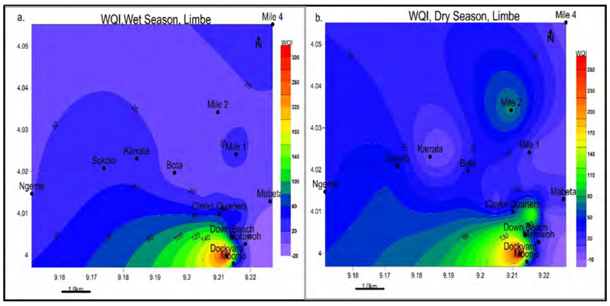

Figure 17: Spatial variation of WQI for a) wet and b) dry seasons; Water is of overall good quality with greater values in the wet season discharge.

Total Hardness (HT): In the study area, HT values were recorded as between 05.04-531.95mg/L in the wet season and 91.50- 570.61mg/L in the dry season as shown in figure 18 and based on the hardness classification of groundwater by Sawyer and McCarty [31] presented in table 15: During the wet season 95% of groundwater is soft, with the exception of Dockyard which has hard water and is close to the Atlantic Ocean. There exist no soft water in the city during the dry season, all groundwater are moderately hard through hard to very hard in Dockyard.

Irrigation water quality (Agro-industrial)

Parameters that are generally considered for evaluation of the suitability of ground water for irrigation were the percent sodium, magnesium hazard, residual sodium carbonate, Kelley's ratio, sodium adsorption ratio, electrical conductivity, total dissolved solid and USSL and Wilcox diagram.

		Wet		Dry	
Hardness	Remark on Quality	No of Samples	% of Samples	No of Samples	% of samples
0-75	Soft	19	95	-	-
76-150	Moderately Hard	-	-	8	40
151-300	Hard	-	-	11	55
>300	Very Hard	1	5	1	5

Table 15: Groundwater Hardness for both wet and dry season.

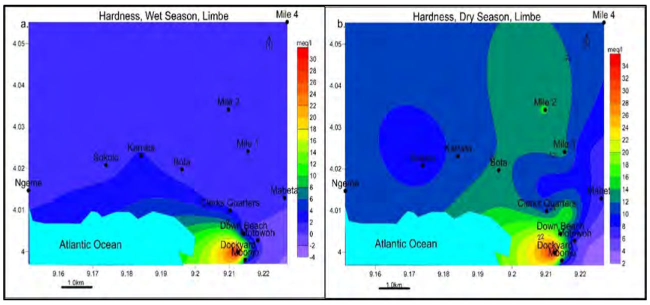

Figure 18: Spatial variation of hardness during: (a) wet season (b) dry seasons. There is a general increase from wet to dry season.

Sodium percentage: Percentage of sodium values ranged from 8.56 to 53.56 in the wet season and 1.67 to 13.41 in the dry season. Based on Wilcox [19] classification show in figure 19; 19 samples,95% fall in the excellent to good category while 1 (Dockyard) fell in the good to permissible category.

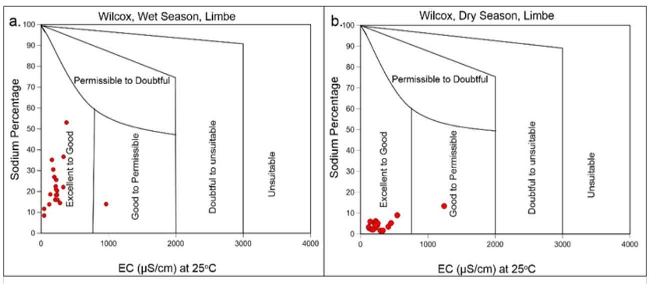

Figure 19: Wilcox diagram showing the suitability for irrigation: 19 (95%) samples fall into the excellent category and 1(5%) is in the good to permissible category for both wet and dry seasons. This signifies that groundwater in Limbe is good for irrigation.

Kelly's Ratio KR: From Kelley ratios presented in table16 which was considered as a basis forrating groundwater for irrigation purposes, values ranged from 0.001 to 0.144 and 0.001 to 0.014 in the wet and dry seasons, with average values of 0.037 and 0.0074 respectively. All samples had KR values less than 1.00 i.e., under the acceptable range and suitable for irrigation purposes [20,32]. The spatial variations presented in figure 20, shows peak values at Dockyard for both seasons.

		Wet		Dry	
	Water Class	No of samples	% of samples	No of samples	% of samples
<1	Suitable	20	100	20	100
>1	Unsuitable	-	-	-	-

Table 16: Water Classes Based on Kelly's Ratio.

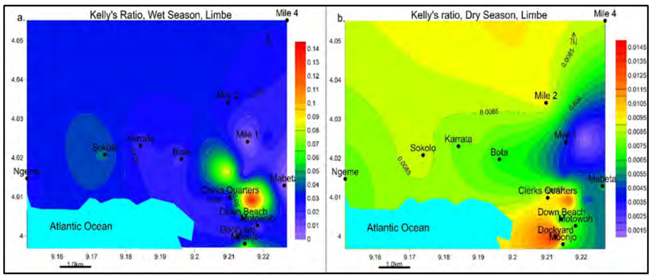

Figure 20: Spatial variation for Kelly Ratio in the a) wet season and b) dry season: The Kelly ratio is higher in the wet season than the dry season.

Residual sodium carbonate: RSC value of groundwater samples were presented in the table 17 and figure 21. The RSC values of the water sample varied from -7.79 - 2.33 meq/l and -2.99 - 0.82 meq/l; 55% and 100% samples had values less than 1.25 meq/l in the wet and dry season respectively and were safe for irrigation while only 45% samples exceeded the values 1.25 meq/l (between 1.25-2.5) indicating that water was moderately suitable for irrigation uses.

RSC	Remark on quality	Wet	%	Dry	%
<1.25	Good	11	55	20	100
1.25-2.5	Doubtful	9	45		
>2.5	Unsuitable				

Table 17: Groundwater Quality based on Residual Sodium Carbonate (RSC)).

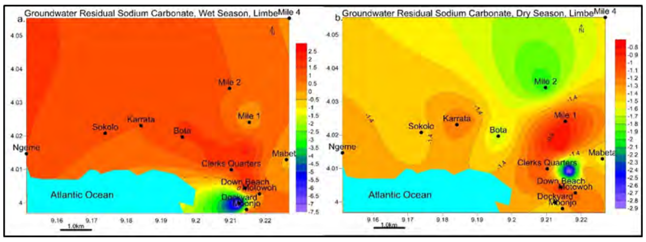

Figure 21: Spatial variation for Residual Sodium Carbonate in the, a) wet and b) dry season: Values are higher in the wet season than the dry season.

Magnesium absorption ratio: MAR values of all the samples varied from 23.34 - 100% in the wet season and 32.12 - 72.29% in the dry season with a mean of 53.41 and 74.31 which was more than 50.00 indicating that Limbe groundwater is not safe and can be classified as not suitable for irrigation uses. Least values were found at Mbonjo area as shown in figure 22.

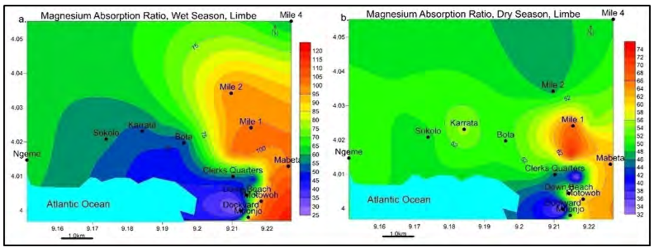

Figure 22: Spatial variation for Magnesium Absorption Ratio in the a) wet and b) dry seasons: There is greater magnesium absorption in the wet season than in the dry season.

Sodium adsorption ratio: The Sodium Adsorption Ratio (SAR) and solute concentration in groundwateris presented in table18 based on the USSL classification for the salinity hazard classes.

Salinity Hazard Class	EC (uS/cm)	Remark of Quality	Wet	%	Dry	%
C0	0-100	Excellent	2	10	-	-
C1	101-250	Very Good	13	65	13	65
C2	251-750	Good	4	20	6	30
C3	751-2250	Doubtful	1	5	1	5

Table 18: USSL Salinity hazard Class for groundwater in Limbe.

The salinity hazard to crop irrigation is determined on the basis of electrical conductivityas presented in figure 23. From the EC values, 10% of the samples in the wet season fell under excellent category (C0 class) but none in the dry season, 65% of the samples in both seasons fell under the very good category (C1 class), 20 and 30% fell in the good category (C2) and in the doubtful category (C3 class), 5% of the samples indicating their suitability for irrigation purposes. Combining the SAR values and electrical conductivities of Limbe groundwater the effect of alkali hazard is classified aspresented in table 19. Most of the ground water samples in the sampling area fell in C1-S1 type (65%), C2-S2 types (20% and 30% in wet and dry season respectively) and were characterized as medium salinity-low alkali hazard and low salinity-low alkali hazard respectively indicating the groundwater is suitable for irrigation under the USSL hazard classification.

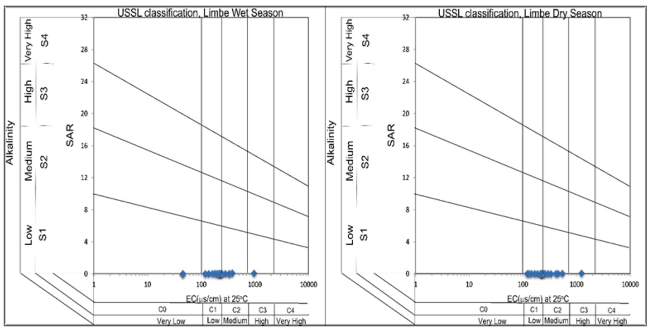

Figure 23: USSL Salinity hazard Class using EC and SAR. a. Wet Season, b. Dry season. The Limbe groundwater is suitable for irrigation.

Sodium Hazard Class	SAR Eq/mole	Remarks	Wet	%	Dry	%
S1	<10	Excellent	20	100	20	100

Table 19: Water Classes Based on SAR for two seasons.

From the spatial variation of SAR shown in figure 24, peak values occur at Clarks Quarters and Dockyard in the wet season and Dockyard in the dry season.

Permeability index: The PI spatial variation is shown in figure 25 and its FAO classification figure 26. 17 samples, 65% fall in the field of class-III: Unsuitable permeability for the wet season; 18 samples 90% Class-II as Good and 2 samples 10% Class-I as excellent for irrigation during the dry season presented in table 20.

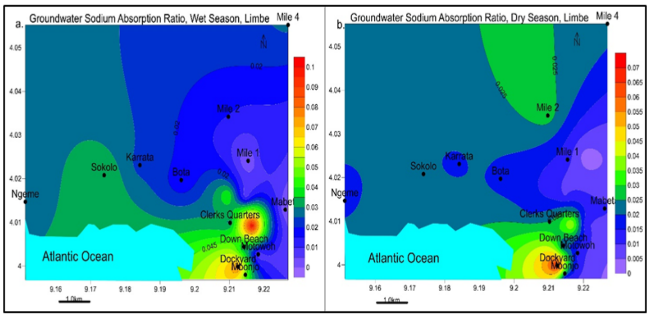

Figure 24: Spatial Variation of Sodium Absorption Ratio for a) wet and b) dry seasons. Values are highest in the wet season.

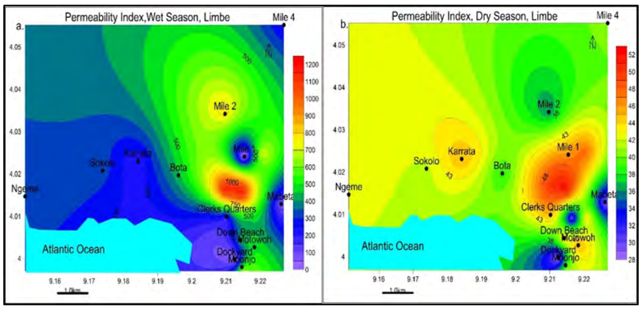

Figure 25: Spatial variation of Permeability Index during: (a) wet season (b) dry seasons. Values are higher in the wet season than in the dry season.

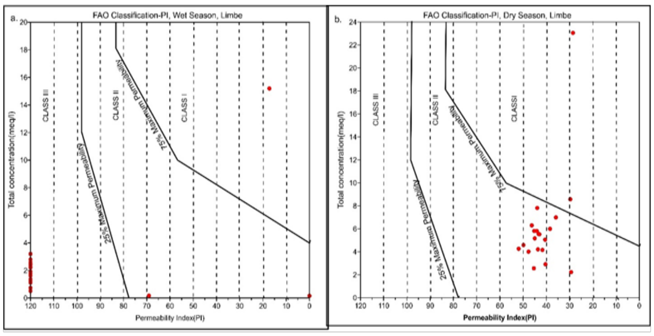

Figure 26: Groundwater FAO classification of groundwater using Permeability Index during: (a) wet season (b) dry seasons. Majority fall in Class III in the wet season while in the dry season, majority falls in Class II.

Classes	PI	Remarks	Wet		Dry	
			No	%	No	%
Class I	>75	Excellent	1	5	2	10
Class II	50-75	Good	2	10	18	90
Class III	25	Unsuitable	17	65	-	-

Table 20: Permeability Index classification of groundwater for two seasons.

Discussion

The physicochemical parameters vary accordingly with season (seasonal control) indicative of a phreatic aquifer. Some values of physicochemical parameters; Temperature, pH, EC and TDS, fall above the permissible limits of [28]. Temperatures of groundwater in Limbe are relatively low and this negates any possibility of magmatic heating as proposed by [33]. The slightly acidic to alkali pH of water in the study area is possibly due to changes in physicochemical conditions that affects the carbon dioxide, carbonate-bicarbonate equilibrium. Elevated TDS above the fresh water limit at Dockyard, 1515 mg/L, indicate seawater intrusion into this coastal aquifer that could result in the groundwater being corrosive, of salty or brackish taste, could cause scale formation that interfers and decreases the efficiency of hot water heaters [34] and could cause gastrointestinal irritation.

Basalts have a primary composition of Feldspars, Ferromagnesian Minerals (Pyroxenes and Amphiboles) and Magnetite (Fe_3O_4) that weather to form residual Kaolinite minerals, Hematite and Goethite with Na^+, Ca^{2+}, Mg^{2+} being leached [16]. The Processes in basaltic weathering, Equations 1-7 are: Hydrolysis, carbonization and solution:

$NaALSi_3O_8 + H_2CO_3 + 4.5H_2O = Al_2Si_2O_5(OH)_4 + Na^+ + HCO_3^- + 2H_4SiO_4$ .... (1)

Albite + Hydrogen ions + water = Kaolinite (clay) + Sodium ions + silicic acid

Or $2NaALSi_3O_8 + 4H^+ + 4H_2O = Al^{3+} + Na^+ + 2H_4SiO_4$ .... (2)

Albite + Hydrogen ions + water = Aluminum ions + Sodium ions + silicic acid

$2KALSi_3O_8 + 2(H^+ + HCO_3^-) + H_2O = Al_2Si_2O_5(OH)_4 + 2K^+ + 2HCO_3^- + 4SiO_2$ .... (3)

Orthoclase + Carbonic acid + water = Kaolinite (clay) + Potassium ions + Bicarbonate + silica

Or $2KALSi_3O_8 + 2H^+ + H_2O = Al_2Si_2O_5(OH)_4 + 2K^+ + 4SiO_2$ .... (4)

Orthoclase + Hydrogen ions + water = Kaolinite (clay) + Potassium ions + silica

Orthoclase: $2KAlSi_3O_8 + 11H_2O = Al_2Si_2O_5(OH)_4 + Si(OH)_4 + 2K^+ + 2OH^-$ .... (5)

Amphibole: $Ca_2Mg_5Si_8O_{22}(OH)_2 + 14CO_2 + 22H_2O = 2Ca^{2+} + 5Mg^{2+} + 14HCO_3^- + 8Si(OH)_4$ .... (6)

Pyroxene: $CaMg(Si_2O_6) + 4CO_2 + 6H_2O = Ca^{2+} + Mg^{2+} + 4HCO_3^- + 2Si(OH)_4$ .... (7)

The leached cations may then enrich the percolating groundwater, giving it its ionic character.

The ionic sequence of the occurrence of major cations and anions in Limbe groundwater is safe for both the wet and dry seasons but for NH_4^+ which is absent in the dry season. The presence of NH_4^+ in the rainy season is due to excess rainfall or runoff transporting sewage and other organic materials that produce ammonium. There is an interchange between HPO_4^{2-} and SO_4^{2-} ions in the wet and dry seasons.

From ionic ratios: SO_4/Cl, Na/Cl, Mg/Cl, Na/HCO_3, Ca/HCO_3, Ca/SO_4, Mg/Ca, Ca/Mg, (Ca+Mg)/(Na+K), HCO_3/∑Anions, NO_3/∑Anions, SO_4/∑Anions, Cl/∑Anions, Na/Na+K; groundwater in Limbe is affected to a great extent by silicate weathering; mostly Ca-silicates and Mg-silicates from the minerals found in basalts with little weathering of Na-silicates, no Na-absorption, some sulfate from external sources, no oxidation of sulphides and no significant anthropogenic contribution of sulfate.

Gibb's diagrams reveals the weathering of the aquifer matrix, is the primary dominant process in the acquisition of ions while atmospheric precipitation is the secondary process controlling the hydrogeochemistry in Limbe. The sources of groundwater ions are; weathering of basaltic rocks (Silicate weathering) that are found in the area and atmospheric precipitation similar to other studies in the basaltic aquiferous formations along the Cameroon Volcanic Line.

The Piper's diagrams indicate the groundwater has a modern age and is being recharged by precipitation. The dominance of Ca-Mg-HCO_3 hydrogeochemical facies in this area could be due to dissolution of gases and minerals, particularly CO_2 and CO_2- related compounds from the atmosphere dissolved in precipitation and during groundwater infiltration through the vadose zone. Processes controlling groundwater solute chemistry are; ion exchange, simple dissolution and Reverse ion exchange. Reverse exchange is not frequently encountered in basaltic terrains, but common in coastal regions. The groundwater in Limbe is recharged uphill on Mount Cameroon, flows through the lava-flow formations on the Mountain slopes and into the low lying shorelines which are in some places below the sea level. During the wet season, sea levels are higher at high tide and the land is submerged by the sea. This results in seawater intruding into the phreatic basaltic fractured rock aquiferous formations in the low lying areas. However, the fresh water volumes from the mountain are so great that during the dry season, the fresh groundwater flushes the seawater back into the ocean and regains its typical basaltic fractured rock aquifer character.

From analysis and interpretation, WQI indicates that 75% of the water is portable for both seasons and 25% are unsuitable. Almost all groundwater in Limbe is soft during the wet season but moderately to very hard in the dry season in the low lying areas; this is due to an increase in the bicarbonate ions which are higher in dry season due to tidal waves coming inland with very low levels of bicarbonate. With respect to irrigation water quality: %Na, KR, RSC, MAR, SAR and PI indicate suitability of groundwater for agricultural use during the dry season. Groundwater is more unsuitable during the wet season as shown by RSC, MAR, Salinity hazard Class (USSL classification) and PI.

Conclusion

In the Limbe coastal area; silicate weathering is the major source of ions into groundwater by the processes of ion-exchange, simple dissolution of the country rock characteristics of groundwater in basaltic terrains and uncommon dissolution (reverse ion exchange) not frequently encountered but common in coastal regionswith seawater intrusion.

There is seawater intrusion in the Limbe coastal area: Low surface elevations, shallow depth-to-water levels, the geology of the formations being made up of mostly porous fractured weathered and un weathered basalts and their proximity to the Atlantic shoreline increases their susceptibility to seawater intrusion.

Water Quality Indices (WQI) show groundwater is within WHO guidelines for potable water at higher elevations for all seasons but unsuitable for agricultural purposes at lower elevations during the wet season.

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